TECHNICAL SERVICE CENTER
Denver, Colorado

Hydroelectric Research and Technical Services Group

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TUNNEL COMMUNICATION TEST RESULTS

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ABSTRACT

Safety and cost issues associated with the lack of reliable beyond-earshot-communication (both within and from within to outside of Reclamation tunnels) often increase tunnel cleaning/ maintenance intervals. In addition, some tunnels fall into the OSHA confined-space definitions. Such spaces generally require reliable communication capability if people are to work in them.

If significantly improved communication can be implemented, enhanced safety and lower tunnel maintenance costs can result. To see if improved voice communication is feasible with current technology, during early 1997, voice radio communication tests were performed at Soap Lake Siphon near Ephrata, Washington, and Azotea tunnel near Chama, New Mexico. The Soap Lake Siphon tests compared the within-tunnel distance performance of 160-MHz-class hand-held radios and 900-MHz-class hand-held radios, as well as providing 600-MHz to 16-GHz radio-frequency received signal-strength vs. distance (propagation) data. At Azotea tunnel the performance of a commercial 400-MHz wireless system, and a low frequency lossy-feeder system operating at 280-520 KHz were also tested. The test data and results are presented in these notes. The 900-MHz-class hand-held radios significantly outperformed the other off-the-shelf communication systems tested and was by far the easiest system to use. The usable communication distance improves as the frequency increases up to 6 GHz. From 6 to 16 GHz the usable communications distance changes little.

In general, the use of higher-frequency radios within Reclamation water conveyance tunnels looks to be a viable communication alternative. Testing showed that at higher frequencies, not yet incorporated into commercial hand-held or easily portable radio systems, reliable, repeaterless communication the entire length of the longest Reclamation tunnels might be feasible.

DISCLAIMER

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INTRODUCTION

Reclamation operates a total of 275 miles of water conveyance tunnels, some of which exceed 10 miles in length. For a number of reasons, people periodically must enter these tunnels, sometimes for extended periods of time, which creates potential hazards for those involved. The Occupational Safety and Health Administration (OSHA) definition of a confined space would include at least some Reclamation tunnels. Thus confined-space regulations, including communication requirements, must be met. While the primary purpose of such communication is worker safety, reliable communication can also expedite work activity.

Presently, in many tunnels communication beyond earshot is non-existent, or impractical. In other situations, voice communication is provided by stringing wires the length of the tunnel, placing repeaters at intervals, or both. These methods are expensive, inconvenient, and add considerable time to the job. The most convenient and least expensive approach would be to use hand-held radios capable of providing reliable communications throughout and external to the tunnel. This investigation was performed to determine the best frequency spectrum to use for tunnel communication, determine the capability of modern hand-held radios, verify the performance of other commercially available communication equipment within Reclamation tunnels, and gather data on Super High Frequency (SHF) radio wave propagation in tunnels for future tunnel communication radio decisions.

Research conducted at the TSC consisted of:

1. Contacting Bureau of Mines communication experts concerning the type of equipment currently employed in underground environments,

2. Searching the literature to learn what work has previously been done in this field,

3. Searching for vendors of commercial equipment of the type deemed most promising. A pair of new technology commercial hand-held radios operating in the 900-MHz frequency range was obtained for evaluation in Reclamation tunnels. (While these radios had an actual operating frequency of 936.6 MHz, they are referred to in this report as 900-MHz radios.)

4. Searching for the specialized laboratory microwave signal source, receiver, and antenna equipment capable of broadband SHF operation. This equipment (see Appendix A) was acquired and used to compile baseline above-ground propagation data for comparison with data taken at the tunnel sites.

Field tests were performed in two different tunnels, Soap Lake Siphon near Ephrata, Washington, and Azotea tunnel near Chama, New Mexico. These two tunnels were picked because they have radically different physical characteristics. Soap Lake Siphon is 25 feet in diameter, 2-1/2 miles long, has major changes of direction in both the vertical and horizontal planes, and has two different type of linings, concrete and steel-lined concrete. Azotea tunnel is 11 feet in diameter, 13 miles long, straight, and is concrete lined.

These tests compared the 5-watt 160-MHz-class hand-held radios in widespread Reclamation use with 3-watt 900-MHz-class hand-held radios. Received signal-strength measurements were also made at a number of SHF to see if there was potential for improved communications at those frequencies. At Azotea tunnel two commercially available confined-space communication systems were also tested: A 2-watt 400-MHz wireless system provided by SAFE ENVIRONMENT ENGINEERING, and a low-power, low-frequency (280-520 kHz) lossy-feeder radio system provided by RIMtech. These systems were operated by the respective manufacturers' representatives. Lossy-feeder systems couple a radio signal into conductors that already exist in the tunnel. As the receiver is always within a few feet of the conductor, reliable communications with very-low-power transmission is possible. Azotea tunnel has no existing conductors, so the signal was coupled into a cable which was unrolled as the test was performed.

CONCLUSIONS

These conclusions apply to the tunnels that were used for these tests. However, the results are indicative of the level of performance that can be expected in similar tunnels.

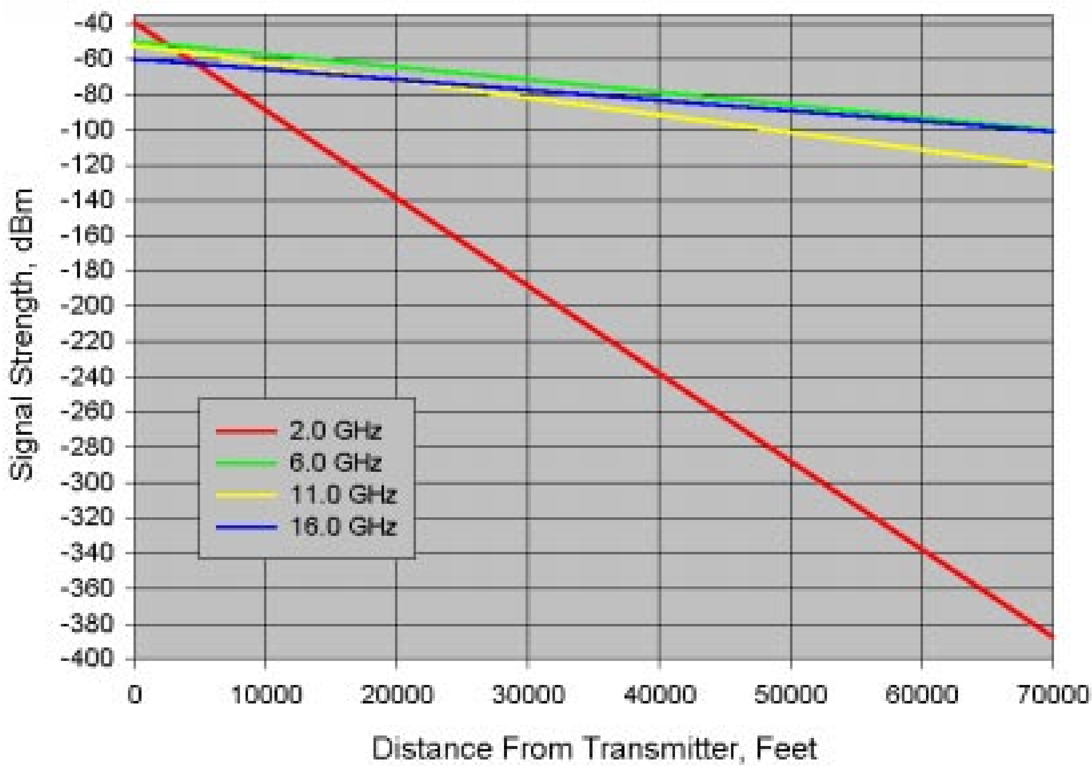
- As expected, the reliable communication range limit of the 5-watt 160-MHz Reclamation hand-held radios was about 0.2 mile (1,000 feet) in both tunnels. Beyond that range they were useless.

- The 3-watt 900-MHz radios provided reliable communication for about 1 mile in Soap Lake Siphon (the maximum test range possible due to water at the bottom of the siphon), and from just outside the entrance of the Azotea tunnel to about 0.8 mile inside the tunnel. With both radios in Azotea tunnel, the reliable communication range was about 1.5 miles. When high-gain directional antennas were added to both radios, the range increased to almost 2 miles.

- The 2-watt 400-MHz wireless system required repeaters at approximately 0.4 mile (2,200 feet) intervals.

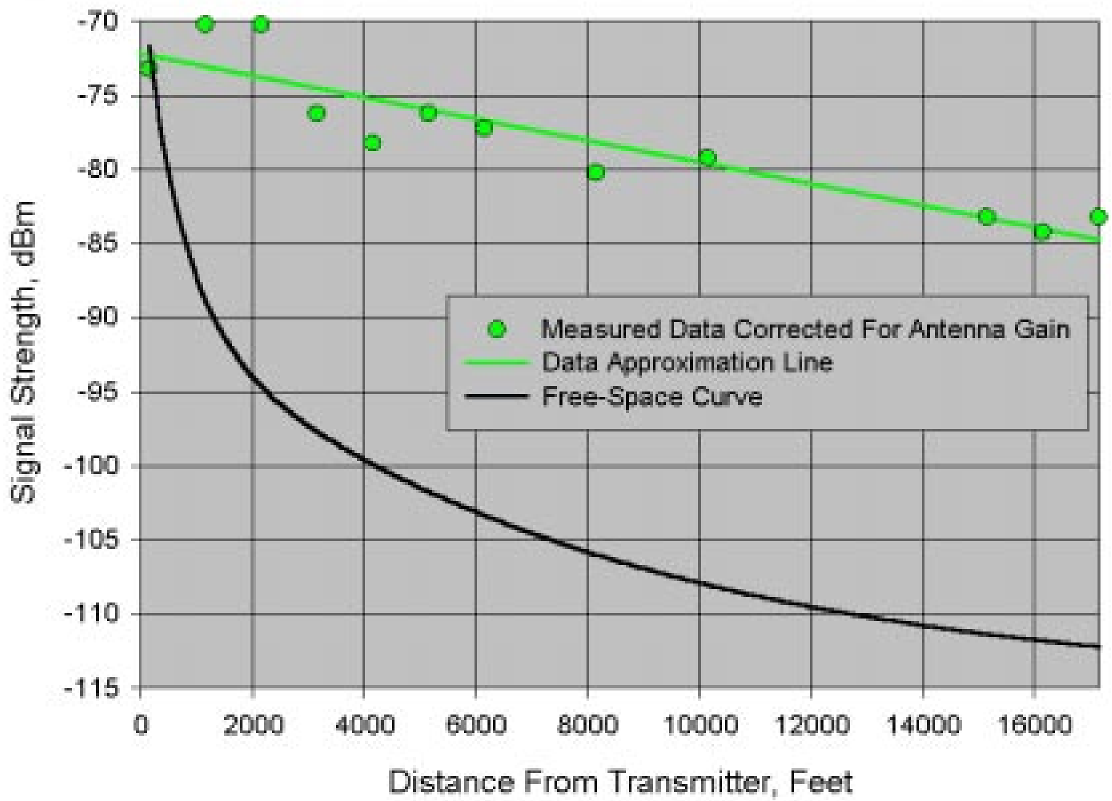
- The lossy-feeder system also required repeaters at approximately 0.4 mile (2,200 feet) intervals. For this system, there was the additional inconvenience of unrolling and re-rolling thousands of feet of wire. The system quit working when an accidental tug on the wire tipped the repeater into the water flowing along the bottom of the tunnel.

- The SHF measurements indicate that for Azotea tunnel (and probably also for similar tunnels), with all radios located inside the tunnel, there exists a band of frequencies between 6.0 and 16.0 GHz at which reliable communication for many miles may be possible. Within this frequency range the received signal level in dBm drops approximately linearly with distance. Extrapolation of that data indicates that for these frequencies the signal loss from one end of the tunnel to the other should be between 40 and 80 db, depending on frequency. Figure 1 shows the extrapolated signal strength for the SHF frequencies used in these tests. Note how rapidly the 2.0-GHz signal is reduced as the distance from the transmitter is increased. However, the 6.0-GHz through 16.0- GHz signals, while starting at a lower level than the 2.0-GHz signal, drop at a much lower rate, so that at great distances down the tunnel much more signal is available to be received than at the lower frequency. See figures 3 and 4 (pages 12 and 13) for the measured data points out to 17,150 feet into the tunnel.



Azotea Tunnel Extrapolated Signal Strength vs. Distance
2.0, 6.0, 11.0, and 16.0-Ghz Frequencies
FIGURE 1

- If this extrapolation reflects the actual end-to-end tunnel losses, the received signal strength would be equal to or better than that of the communication system in free-space. Thus a system at these high frequencies will work as well or better in the tunnel than in free space. As an example of this improvement, figure 2 compares the free-space signal strength with the measured signal strength (corrected for antenna gain) at 6.0 GHz. See Appendix B for the free-space signal strength calculation procedure.



Azotea Tunnel 6.0-GHz Free-Space/Measured Signal Strength Comparison Corrected for Antenna Gain

Figure 2

- 3-watt radios operating between 6 and 16 GHz should provide reliable communication for the entire 13-mile length of the tunnel. For instance, even without high-gain antennas, at 6.0 GHz the expected signal strength would be approximately -97 dBm with a 3-watt radio. This number is calculated by starting with the 13-mile signal strength of -100 dBm from figure 1, subtracting the total antenna gain of 22.2 dB (11.1 dB at each end of the transmission path, from Appendix B, Table B-1), and adding 24.8 dB for the transmitter output power increase to 3 watts from the 10 mW used in these tests. This -97 dBm signal strength is well within the capabilities of present microwave receiver technology. The receiver used in these field tests can receive signals lower than -120 dBm.

- An antenna or repeater located just inside the tunnel may be necessary for communication from the outside to the far end of the longer tunnels.

RECOMMENDATIONS

These recommendations reflect the state of existing commercial off-the-shelf technology. As off-the-shelf hand-held radios become available that operate at frequencies in the several GHz range, these recommendations will need to be revised to account for the advancement in technology.

At the present time there is no single communication system that will work optimally in all of Reclamation's water conveyance tunnels. Repeaterless systems are preferred over repeater systems. As was demonstrated in these tests, repeaters are additional equipment asking for a mishap. However, for long tunnels, systems that utilize repeaters may be required.

For tunnels less than 500 feet in length, the 5-watt 160-MHz-class of hand-held radios in widespread Reclamation use are recommended. They work fine, and there is no reason to incur the expense of more sophisticated systems. For communication distances in tunnels up to about 1 mile, 900-MHz-class hand-held radios are recommended. The Hydroelectric Research and Technical Services Group (D-8450) has purchased a pair of these radios and has obtained the proper license. They are available for loan to Reclamation offices. We would encourage Reclamation personnel to borrow these radios and experiment in their own tunnels to determine how far and under what conditions they work.

For communication distances greater than 1 mile in length, there is at present no simple, inexpensive solution. Existing, off-the-shelf technology dictates the use of a system with repeaters. Our test data indicate that, for the same transmitter output power and receiver sensitivity, fewer repeaters will be needed the higher the frequency of the communication system. A system using the 900-MHz-class hand-held radios used in these tests would require repeaters at approximately one-mile intervals.

BACKGROUND

Reclamation operates 275 miles of water conveyance tunnels, some of which are miles in length. These tunnels must be periodically inspected, repaired, and/or cleaned. In these operations, worker safety is a major issue. OSHA requires that workers inside a confined space be able to communicate with workers outside the confined space (see OSHA confined space standard 1910.146, paragraph (d)(4)(iii) for communications equipment requirements). The OSHA definition of a confined space would include most, if not all, Reclamation tunnels. This requirement often dictates that overhead telephone lines, or some other hard-wired communication system be installed prior to, and removed after the inspection/repair. Such installations/removals substantially increase the costs of the operation, which, because of budgetary constraints, can limit how often these tunnel operations are performed.

For example, cleaning a tunnel over a decade ago at Judge Francis Carr Powerplant increased generation revenues by nearly $2.2 million per year. With time, the tunnel losses have again increased and the generation revenues have dropped to essentially where they were before the cleaning. Despite the potential increase in generation revenue, the safety issues (primarily the costs of reliable communication) and other costs associated with that cleaning, the tunnel has not been cleaned since. The one-time expense of a reliable communication system will result in ongoing savings every time a tunnel, Reclamation-owned/operated or otherwise, is inspected, repaired, or cleaned. See appendix F for a **WATER OPERATION AND MAINTENANCE BULLETIN** article discussing tunnel inspection issues.

Preliminary Work

D-8450 personnel conducted a survey of Reclamation offices, where a great deal of interest was shown in reliable wireless tunnel communication. Several tunnels were offered as test locations.

Bureau of Mines communications experts were contacted concerning the type of communication equipment currently employed in underground environments, a literature search was performed to determine what has previously been learned in this field, and a vendor search was undertaken to determine what type of commercial equipment for underground communication was currently available. The result of this preliminary work was:

- Communications in tunnels is accomplished at either very low frequencies (below those used for commercial AM radio broadcasting), using wires that run the length of the tunnel, or high frequencies using radios, with repeaters as necessary.

- The literature suggested that the best frequencies to use for hand-held radio communication would be in the several GHz microwave frequency region, but off-the-shelf commercial hand-held or compact, portable equipment is not yet available at those frequencies.

- The highest frequency commercial hand-held radio equipment available was 3-watt, 900-MHz-class hand-held radio tranceivers.

- Two companies were contacted that expressed interest in testing their systems in Reclamation tunnels. These were RIMtech and SAFE ENVIRONMENT ENGINEERING. They participated in the tests at Azotea tunnel.

<u>Previous SHF Research</u>

Previous research into the propagation of SHF radio waves in a tunnel indicates that at high enough frequencies radio propagation inside tunnels should improve dramatically because the wavelength becomes small compared to the tunnel size (see Appendix F, excerpts from Jakes, **Microwave Mobile Communication,** and Yocoud, **Foundations of Mobil Radio Engineering**). When this condition is met, propagation along the tunnel axis approaches that of free space, while off-axis propagation is increasingly reflected from, rather than absorbed by, the tunnel walls, especially if the tunnel lining contains an electrical conductor, such as steel reinforcing rods. The tunnel behaves as if it were a waveguide, even allowing propagation to some extent around curves.

Commercial, off-the-shelf hand-held radios are presently limited to an upper frequency of about 940 MHz. While commercial equipment operating at higher frequencies does exist, this equipment is either large, expensive, and/or was designed for other applications. Besides being costly and difficult to use in tunnels, such equipment is a great overkill for Reclamation's purposes. However, at these high frequencies the technology changes rapidly, and new commercial equipment is becoming available on a regular basis.

PURPOSE OF FIELD TESTS

Based on previous research, and the current state-of-the-art, it was decided to perform field tests to establish what frequencies, if any, show promise of providing reliable tunnel communication for long tunnel lengths, and to become acquainted with and compare the performance of commercially available 900-MHz hand-held-radios with existing Reclamation 160-MHz radios and two existing commercial tunnel communications systems.

TUNNEL DESCRIPTIONS

Many Reclamation regions and area offices showed an interest in the development and demonstration of a reliable radio system for use in tunnels. To support this effort they were willing to let us perform tests at their facilities.

Two tunnels were chosen because of their different physical characteristics, as well as availability for the tests: Soap Lake Siphon (see Appendix D), and Azotea tunnel (see Appendix E). Azotea tunnel is about as simple as a tunnel can be – an 11-foot-diameter straight bore for nearly 13 miles, with a simple concrete lining and no electrical conductors in the structure. On the other hand, Soap Lake Siphon is very large (approximately 25 feet diameter-- the diameter changes slightly twice along its length), is lined with concrete, has steel in part of the tunnel lining, and, between the longest receiver/transmitter separations attained in this test, has three bends that cover a nearly 120 degree angle in the horizontal plane, and four bends in the vertical plane. These vertical bends encompass an elevation drop of nearly 200 feet.

TEST PROCEDURE

Prior to performing tests in the tunnels, the SHF test equipment was individually checked for proper operation in the Denver laboratories. Mobile receiver and transmitter instrumentation packages were set up on the street just outside the laboratory, and baseline signal-strength measurements were made at various locations along the street. This baseline data provides a very approximate indication of the free space attenuation at specific SHF, and were taken for comparison with the tunnel data. The arrangement of these packages, including manufacturer and model information, appear in Appendix A. The data obtained appear in Appendix C, Table C-1. A photograph of the transmitter package appears in Appendix E, Figure E-1.

At Soap Lake Siphon the receiver instrumentation package was set up on a table just inside the tunnel, and a transmitter instrumentation package was set up on a two-wheel hand truck. At Azotea tunnel the transmitter and receiver packages were reversed, with the transmitter package set up on a table just inside the tunnel entrance and the receiver package set up on an Ingersoll-Rand Bobcat. See Appendix E, Figures E-4 and E-5 for photographs of these packages in the Azotea tunnel. In both tunnels the mobile equipment was moved to the test position, signal strength measurements were made at the various frequencies, and the clarity of voice communication through the radios was noted. The mobile platform was then moved to the next test position.

Test frequencies of 600 MHz, 900 MHz, 2.0 GHz, 6.0 GHz, and 11.0 GHz were chosen because they were near those used in previous research, which allowed the results of these tests to be compared with those of previous research. Additionally, because the test equipment allowed measurements up to 16 GHz, data were taken at this frequency also. The transmitter power output at all frequencies was +10 dBm. Standard Motorola MT 2000 series 3-watt-output, 900-MHz hand-held radios were used for general voice communication and were compared with standard Reclamation 160-MHz class hand-held radios.

In addition, at Azotea tunnel, a 2-watt, 400-MHz wireless system provided by SAFE ENVIRONMENT ENGINEERING, and a 280-520 KHz (below the AM broadcast band) lossy-feeder conductor FM radio system provided by RIMtech were also tested. These two systems were installed and operated by representatives of the respective companies.

DISCUSSION OF TEST RESULTS

Data Analysis

1. Baseline Data

For the test frequencies of 900 MHz and above, tables 1 through 5 compare the above-ground baseline signal-strength data with the theoretical signal strength that would be produced using isotropic antennas in a true free-space environment. Such an environment does not exist on the surface of the earth, but free-space calculations are useful as references with which to compare actual radio propagation data. The baseline data in these tables has been corrected for the gains of both the transmitting and receiving antennas. The 600-MHz data are not presented. While baseline data were taken at 600 MHz, this frequency is significantly below the antenna cutoff frequency, and the antenna gain was not known. Notes 1 and 2 of table 1 apply also to tables 2 through 5. See Appendix B for the procedure for calculating the free-space signal strength.

It will be noted that while there is general agreement between the corrected baseline signal strengths and the free-space signal strengths, the baseline numbers are lower than the free-space numbers. This discrepancy exists because the measurement environment was not a true free-space environment. Both transmitting and receiving antennas were within a few feet of the ground, and there were buildings and automobiles along the propagation path which absorbed and deflected the radio signals. At all frequencies the discrepancy starts small and rises as the antenna separation distance increases.

Table 1
900-MHz Free-Space and Baseline Signal Strengths

Distance, Ft.	Free Space Signal Strength[1]	Baseline Signal Strength, dBm[2]
10	-31.17	-32.00
1,000	-71.17	-79.5
2,250	-78.21	-89.3
3,040	-80.82	-109.0

1. The Free Space signal strength is a theoretical reference level for an isotropic radiator with an output power of +10 dBm.
2. The signal strength numbers have been corrected for the gain of the horn antennas at both the transmitter and receiver. The power output to the transmitting horn antenna was +10 dBm.

Table 2
2.0-GHz Free-Space and Baseline Signal Strengths

Distance, Ft.	Free Space	Baseline Signal Strength, dBm
10	-38.10	-39.2
1,000	-78.10	-82.9
2,250	-85.14	-102.0

3,040	-87.76	-102.0

Table 3
6.0-GHz Free-Space and Baseline Signal Strengths

Distance, Ft.	Free Space	Baseline Signal Strength, dBm
10	-47.64	-49.7
1,000	-87.64	-89.2
2,250	-94.69	-107.5
3,040	-97.30	-109.2

Table 4
11.0-GHz Free-Space and Baseline Signal Strengths

Distance, Ft.	Free Space	Baseline Signal Strength, dBm
10	-52.91	-56.1
1,000	-92.91	-90.6
2,250	-99.95	-119.4
3,040	-102.57	-112.4

Table 5
16.0-GHz Free-Space and Baseline Signal Strengths

Distance, Ft.	Free Space	Baseline Signal Strength, dBm
10	-56.16	-63.6
1,000	-96.16	-101.4
2,250	-103.21	-115.2
3,040	-105.82	-119.7

Table 6 shows the difference between the free-space signal strength and the baseline signal strength for the various frequencies at the longest distance, 3040 feet. At all frequencies except 16.0 GHz, this difference decreases as the frequency increases. As the frequency increases, the height above ground in wavelengths of the antenna increases, making the transmission path a better approximation to a true free-space path.

Table 6
Difference Between Free-Space and Baseline Signal Strength at 3,040 Feet.

Frequency, GHz	Signal Strength Difference, dBm
0.900	28.18
2.0	14.24
6.0	11.90
11.0	9.83
16.0	13.88

2. Soap Lake Siphon

Table 7 compares the Soap Lake Siphon data with the baseline data for all test frequencies at approximately the same distance (2,200 feet). Since all data were taken using the same antennas, no correction for antenna gain is necessary.

At all frequencies above 900 MHz the signal strength in the tunnel was greater than the baseline signal strength. Communication in the tunnel exceeded the baseline performance in spite of several direction and elevation changes between the transmitter and receiver. A portion of the siphon has a steel lining, which helps explain the propagation around the curves.

Table 7
Comparison of Baseline Signal Strength Data with Soap Lake Siphon
Signal Strength Data at a distance of approximately 2,200 feet

Frequency (GHz)	Baseline, dBm	Soap Lake Siphon, dBm
0.600	-101	-102
0.900	-75.3	-61.0
2.0	-84.8	-61.0
6.0	-85.3	-61.0
11.0	-85.0	-79.0
16.0	-83.8	-79.0

Figure 3 is a plot of the measurements made at Soap Lake Siphon. For this siphon, at the maximum measurement distance, the 900-MHz signal was strongest. While the signal strengths appear to be converging at the farthest distance measured, no general conclusions can be drawn

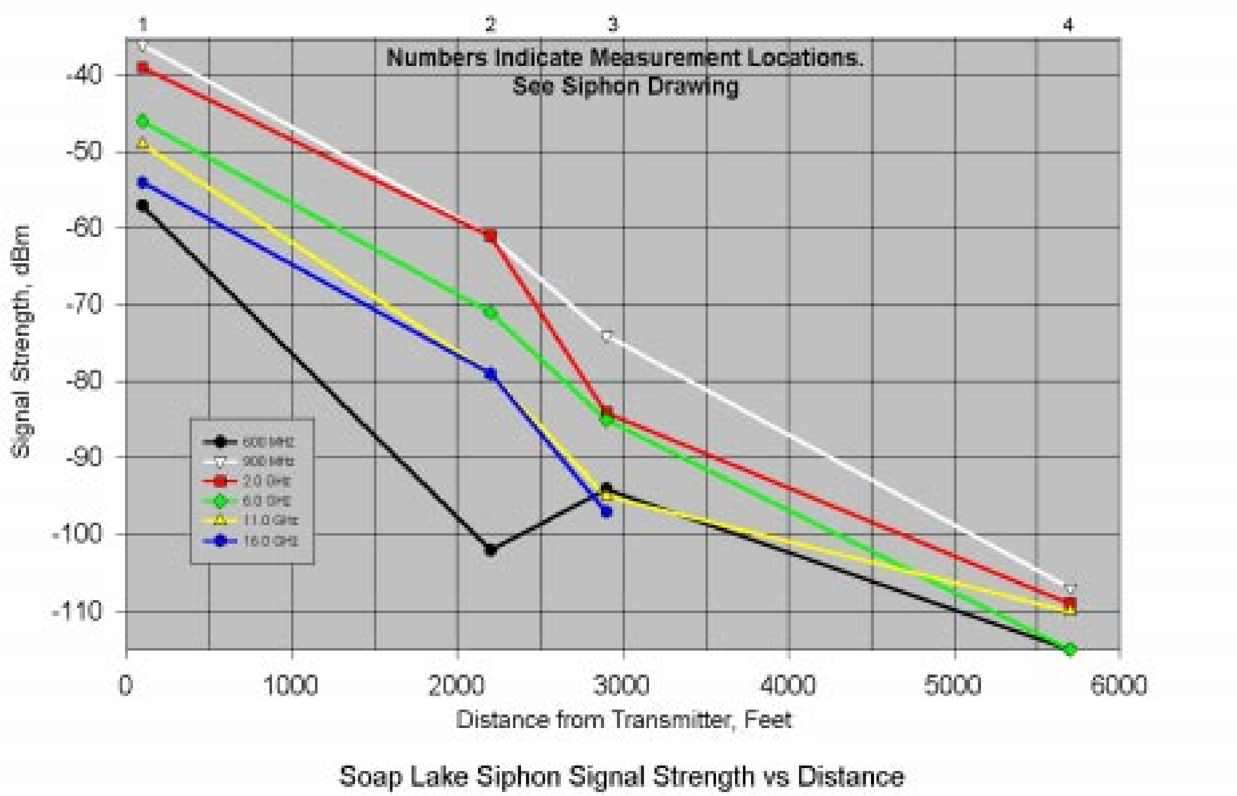


Figure 3

because the measured signal strengths actually diverged at the first measurement point after a tunnel direction change (location 2).

3. Azotea Tunnel

Table 8 compares the Azotea tunnel data with the baseline data for all test frequencies at approximately the same distance (2,200 feet). Again, no correction for antenna gain is necessary.

Table 8
Comparison of Baseline Signal Strength Data with Azotea Tunnel
Signal Strength Data at a Distance of Approximately 2,200 Feet

Frequency (GHz)	Baseline, dBm	Measured, dBm
0.600	-101	Too small to be measured
0.900	-75.3	-85.0
2.0	-84.8	-48.0

6.0	-85.3	-48.0
11.0	-85.0	-52.0
16.0	-83.8	-62.0

As with Soap Lake Siphon, the signal strength inside the tunnel is much greater than the baseline, indicating that the tunnel is indeed behaving like a waveguide.

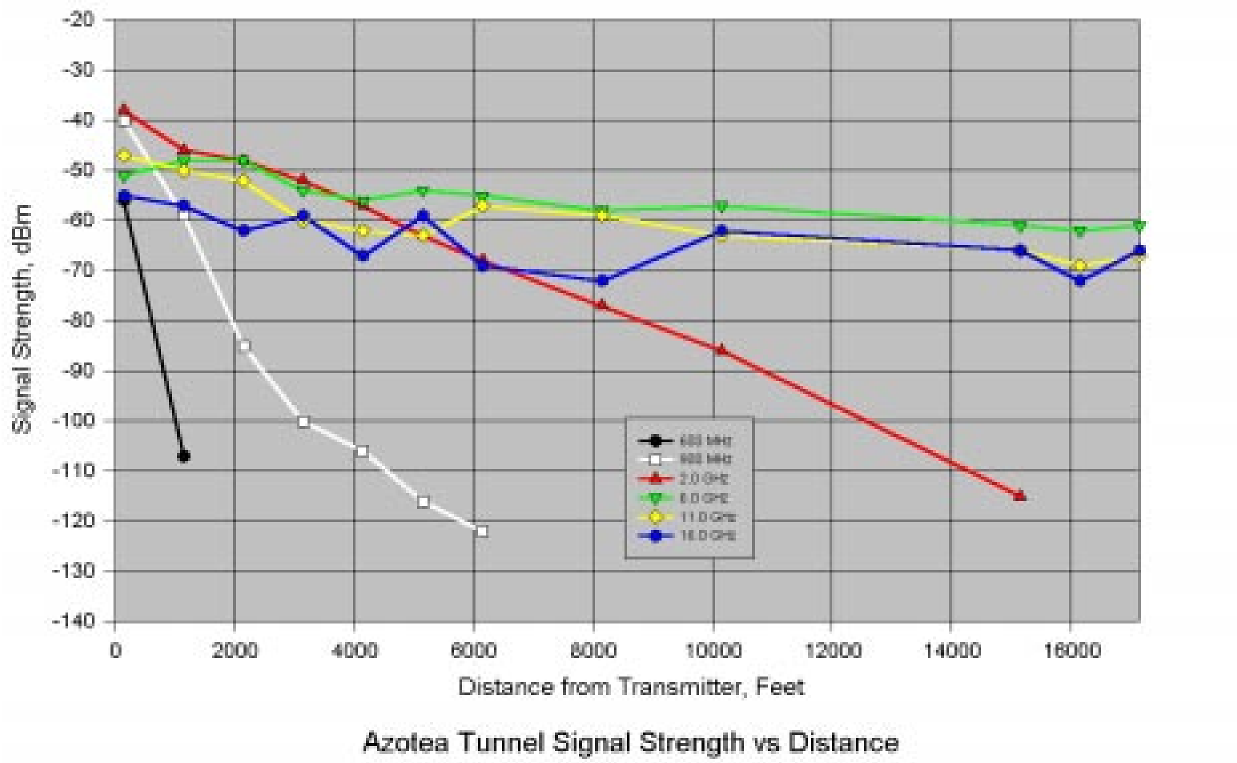
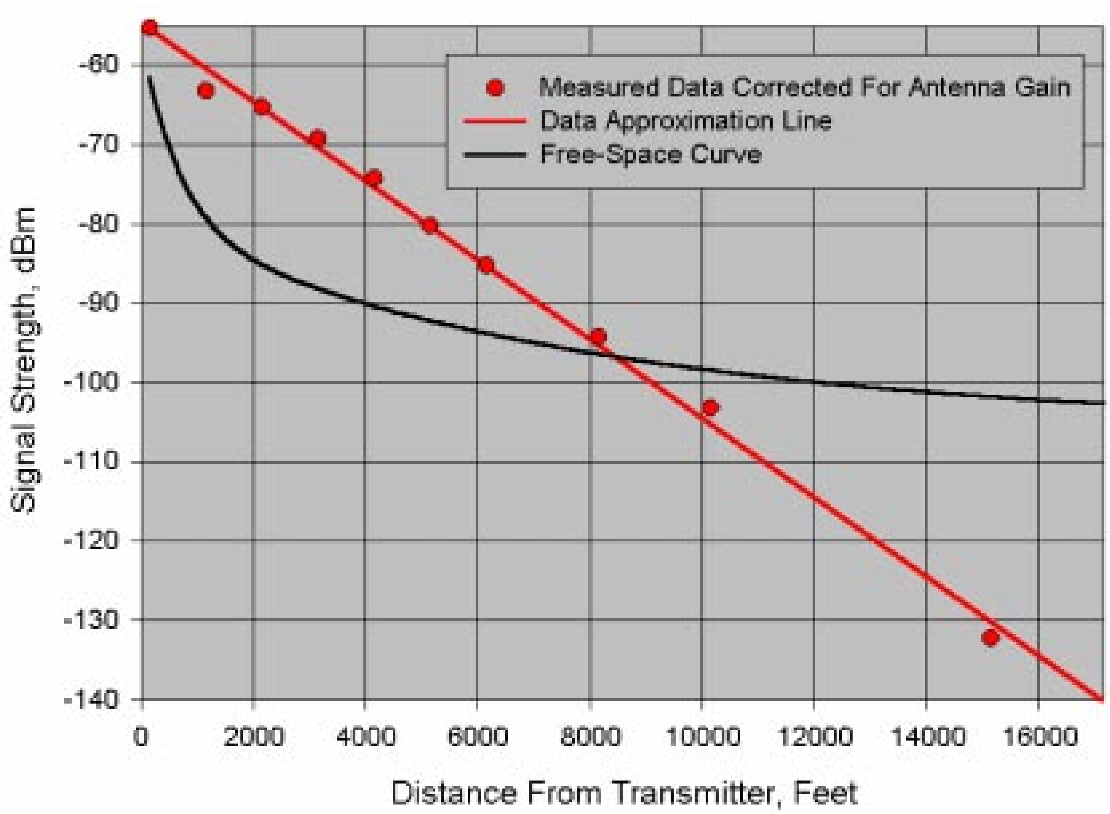


Figure 4

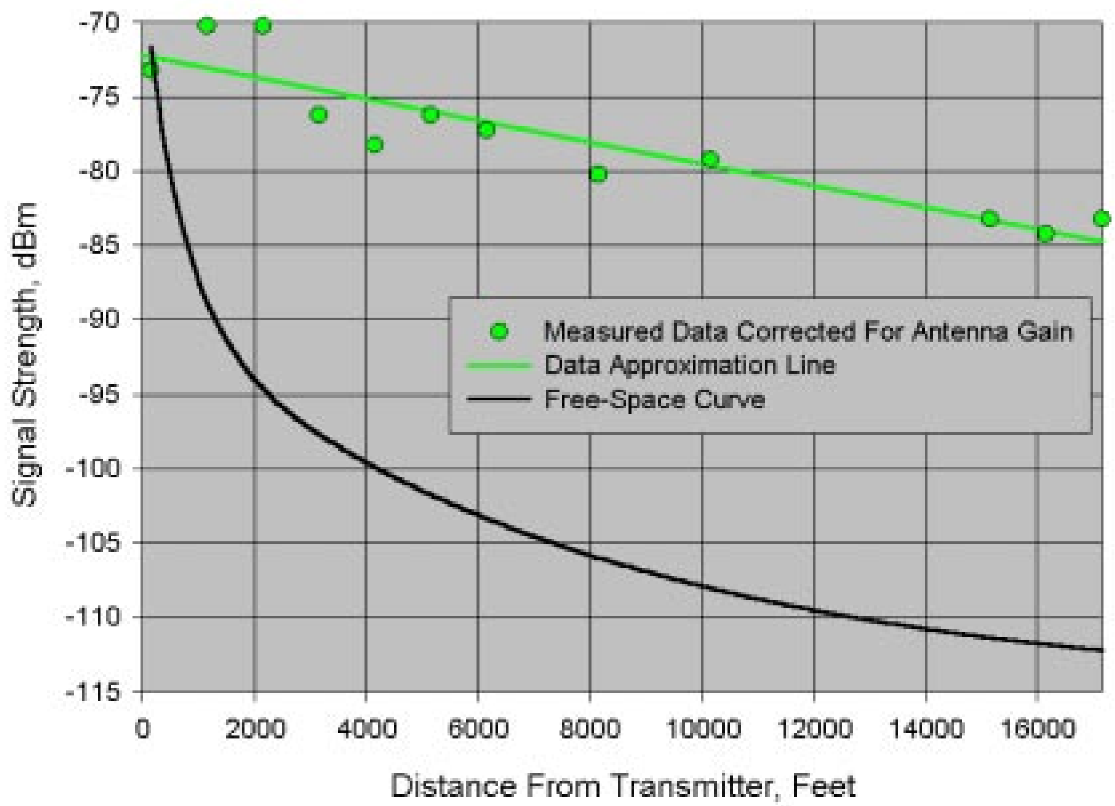
Figure 4 shows plots of the signal strength in Azotea tunnel at the various test frequencies as a function of distance. It is clear that best results are achieved with frequencies between 6.0 GHz and 16.0 GHz.

What is not obvious from Figure 4 is just how the signal strength at each frequency compares with the free-space signal strength. Figures 5 through 8 show this comparison. At 2.0 GHz the tunnel signal strength is initially higher than the free-space signal strength, but as the distance increases the tunnel strength falls below the free-space strength. On the other hand, at the higher frequencies the tunnel signal strength is initially lower than the free-space signal strength, but as the distance increases the tunnel strength crosses above, and remains above the free-space strength by a substantial amount.



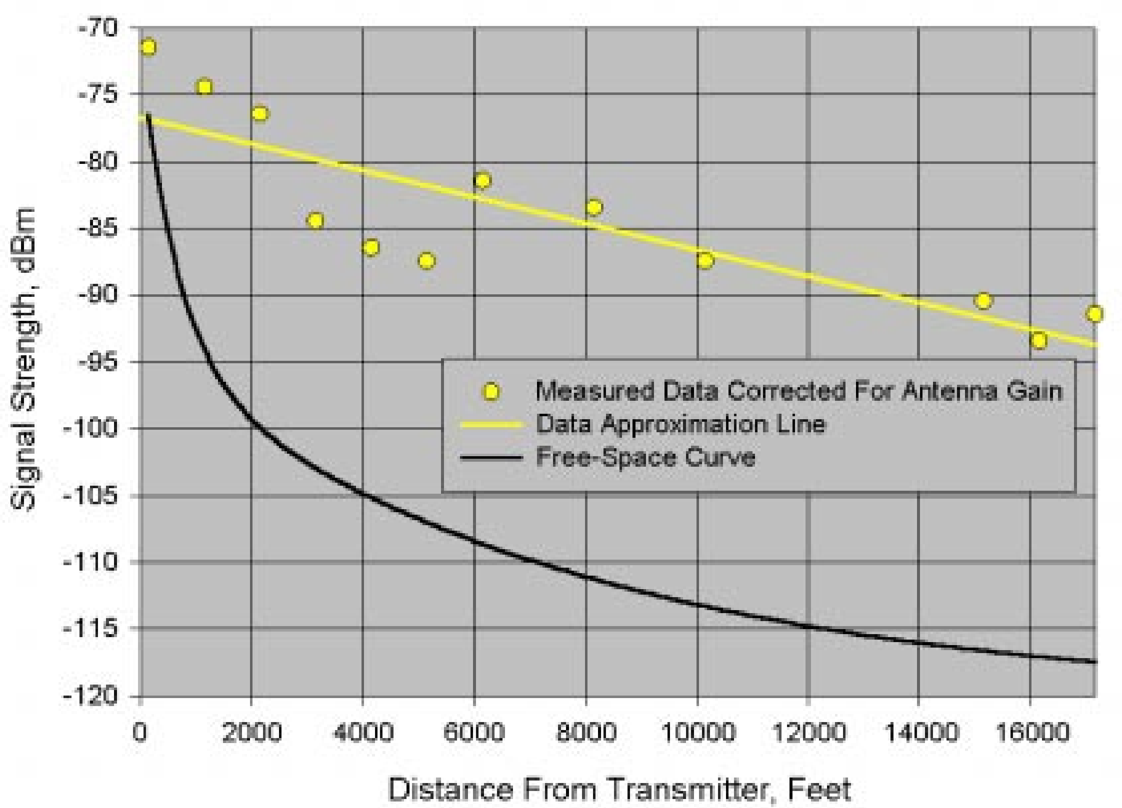
Azotea Tunnel 2.0-GHz Free-Space/Measured Signal
Strength Comparison Corrected for Antenna Gain

Figure 5



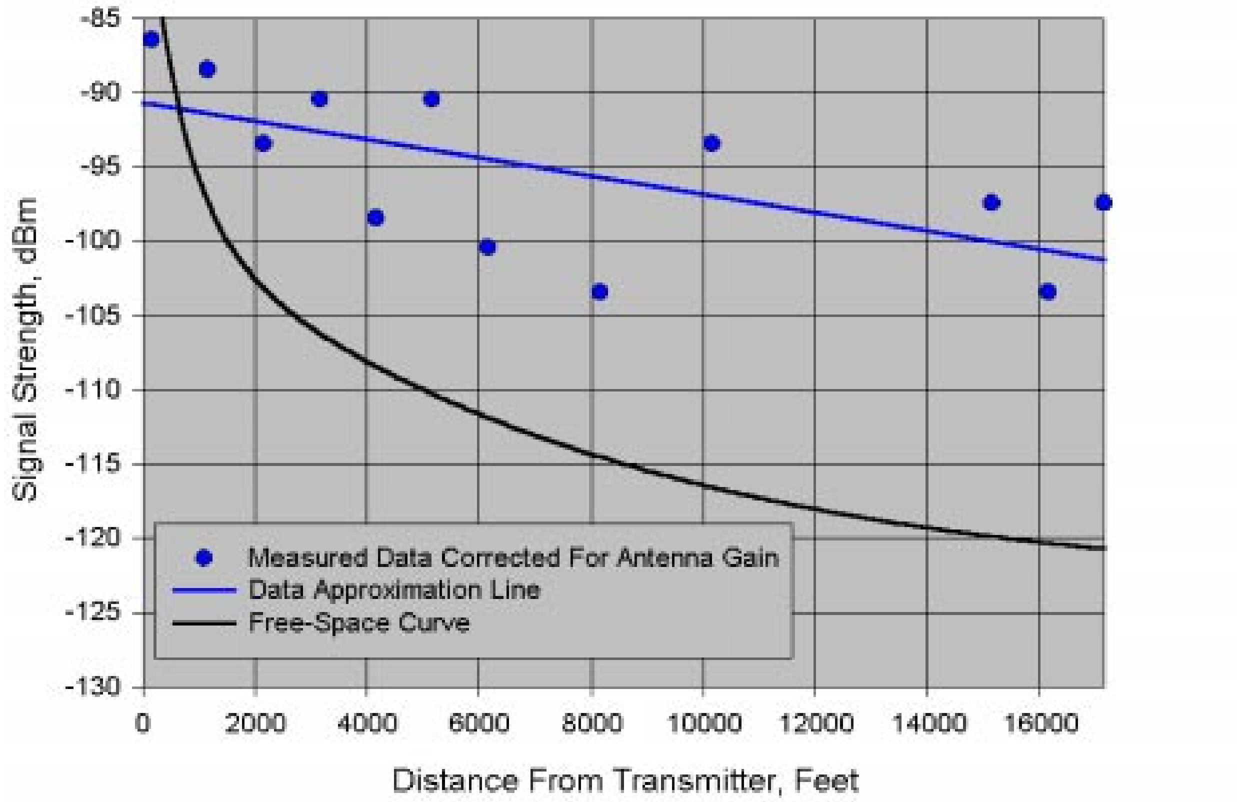
Azotea Tunnel 6.0-GHz Free-Space/Measured Signal Strength Comparison Corrected for Antenna Gain

Figure 6



Azotea Tunnel 11.0-GHz Free-Space/Measured Signal
Strength Comparison Corrected for Antenna Gain

Figure 7



Azotea Tunnel 16.0-GHz Free-Space/Measured Signal
Strength Comparison Corrected for Antenna Gain

Figure 8

The signal strength vs. distance plots (Figure 4) show that, as expected, the larger the separation between transmitter and receiver packages, the smaller the received signal. If the received signal becomes too small, the receiver will not be sensitive enough to provide a clean, intelligible voice signal to the user. Consequently, without repeaters, every radio system will cease to provide reliable communications at some distance. High-gain antennas can increase this distance somewhat. For a given tunnel, the precise distance depends on the transmitter power, antenna gain, and the receiver sensitivity, with receiver sensitivity being the single-most important factor.

As an example, at 900 MHz the received signal strength drops about 20 db from a distance of 150 feet into the tunnel to about 17,000 feet into the tunnel. Increasing the transmitter output power by 20 db (to a battery-draining 300 watts) would only add about 17,000 feet to the communication distance. However, increasing the receiver sensitivity by 20 db (a voltage factor of 10, but no significant additional battery drain) would add the same 17,000 feet to the useful communication distance.

The signal strength vs. distance plot for Soap Lake Siphon (Figure 3) shows that turns in the tunnel cause considerable signal loss at most of the frequencies tested. The rise that occurred at 600 MHz is due to reinforcing reflections for this particular tunnel and transmitter/receiver locations. At Soap Lake Siphon the losses limited the reliable communication distance to 1 mile. It should be noted that a frequency of 11 GHz resulted in the smallest attenuation of all the frequencies tested. However, the difference between performance at 900 MHz and 11 GHz was not very significant. The presence of steel reinforcing can be expected to improve the communications performance in tunnels with many turns. Even though the signal strengths are reduced around each bend in the tunnel, the tunnel is still functioning as a fairly good waveguide. As shown in the siphon drawing (Appendix D), at the greatest distance, for the radio signal to reach the receiver it had to travel around seven major bends.

At Azotea tunnel, it is clear that frequencies between 6 GHz and 16 GHz had considerably less signal loss with distance than the lower frequencies tested. In fact, at 6 GHz the loss was only 10 dB over a distance of more than 3 miles, a result that is significantly better than free space propagation. If that rate of signal loss were to continue for the rest of the tunnel length, there would only be about a 21-dB loss over the entire 13-mile length of the tunnel. If they were available, 3- to 5-watt hand-held radios operating at this frequency might very well provide repeaterless communications in very long, straight tunnels.

It was noted in both tunnels that small movements of the receiving antenna had negligible effects on the received signal strength. The only noticeable effect was that significantly reduced signal strengths occurred when the receiving antenna was placed within a couple of inches of the tunnel wall. As long as the transmitting and receiving antennas were pointed toward each other, the signal strength was not strongly dependent on precise antenna orientation.

Performance of Commercially Available Radio Systems

The 5-watt, 160-MHz radios were not useful much beyond 0.2 mile (1,000 feet) in either tunnel, and at that distance communications were not clear. These radios would probably provide reliable communications if the tunnel were 500 feet or less in length.

The 2-watt, 400 MHz and low-frequency, lossy-feeder commercial systems provided satisfactory communications after they were adjusted properly, but both needed repeaters for communication over distances greater than about 0.4 mile (2,200 feet). If all other factors are equal, the more components there are in a system, the less overall reliability there is in the system. This issue was brought home when an accidental tug on the unrolling cable of the RIMtech system tipped the repeater into the water, ending communications through that system. This example illustrates a general problem of repeater-type systems when used for temporary installations. These types of systems may perform quite well when permanently installed, but extra care must be taken for temporary installations to prevent the inadvertent disabling of the communication system. Lossy-feeder systems such as that provided by RIMtech may work well if there is existing conduit or wires in the tunnel to which the communication signal can be coupled.

The 3-watt, 900-MHz radios worked well, and over the longest non-repeater-augmented distance of any of the systems tested. At Soap Lake, the 900-MHz radio provided reliable communication over the entire 1 mile distance tested, though audible noise was present after about 0.75 mile. The test distance was limited to 1 mile because of water filling the bottom of the siphon. The size of the tunnel and the smallness of the wavelength seemed to make the tunnel appear as a fairly good waveguide. While the turns had a noticeable degrading effect on the received signal, reliable communication was maintained over the entire distance. See Appendix D for a diagram of Soap Lake Siphon which shows the measurement locations.

In the straight Azotea tunnel, communications at 900 MHz were maintained from just above the tunnel opening to about 0.8 mile into the tunnel. When the outside radio was brought into the tunnel, the range increased to about 1.5 miles with only the built-in several-inch-length (rubber-ducky) antennas. Adding external YAGI antennas at both the receiver and transmitter locations increased the range to about 2 miles.

Based on these results, 3-watt, 900-MHz radios should provide reliable communication in most tunnels for distances between 0.5 and 1.0 mile, with reliable communication possible for up to 2.0 miles in some cases.

FURTHER RESEARCH

The commercial availability of hand-held radio products operating in the approximately 5-15 GHz frequency range should continue to be monitored for new developments. If a commercial set is developed it should be obtained and its communication effectiveness ascertained in as many different tunnel configurations as feasible. An actual radio operating at conventional hand-held radio output power would increase the communication distance in all tunnels over that obtainable with the very-low-power SHF signal source used in these tests.

Since the technology exists, if appropriate-frequency commercial hand-held radios are not available, it is possible to configure the equivalent of such radios. For instance, there exist products developed for the amateur radio market that, when used in conjunction with 2-meter (144-MHz) amateur radio transceivers, provide for portable operation at GHz frequencies. The acquisition of a prototype system based on the amateur radio approach, which uses the existing Reclamation 160-MHz radios, and/or the development of a new system for testing in Reclamation tunnels, should be pursued. Once manufacturers perceive a viable market, commercial equipment may become available quickly.

Reclamation should encourage the development of a SHF portable communication system. Such a system would not only benefit Reclamation by providing reliable, possibly repeaterless communication in our water-conveyance tunnels, or inside dam structures, but could also find widespread use in other government agencies and the private sector anytime reliable wireless communication is necessary in underground structures.

APPENDIX A

EQUIPMENT LIST AND TEST ARRANGEMENT

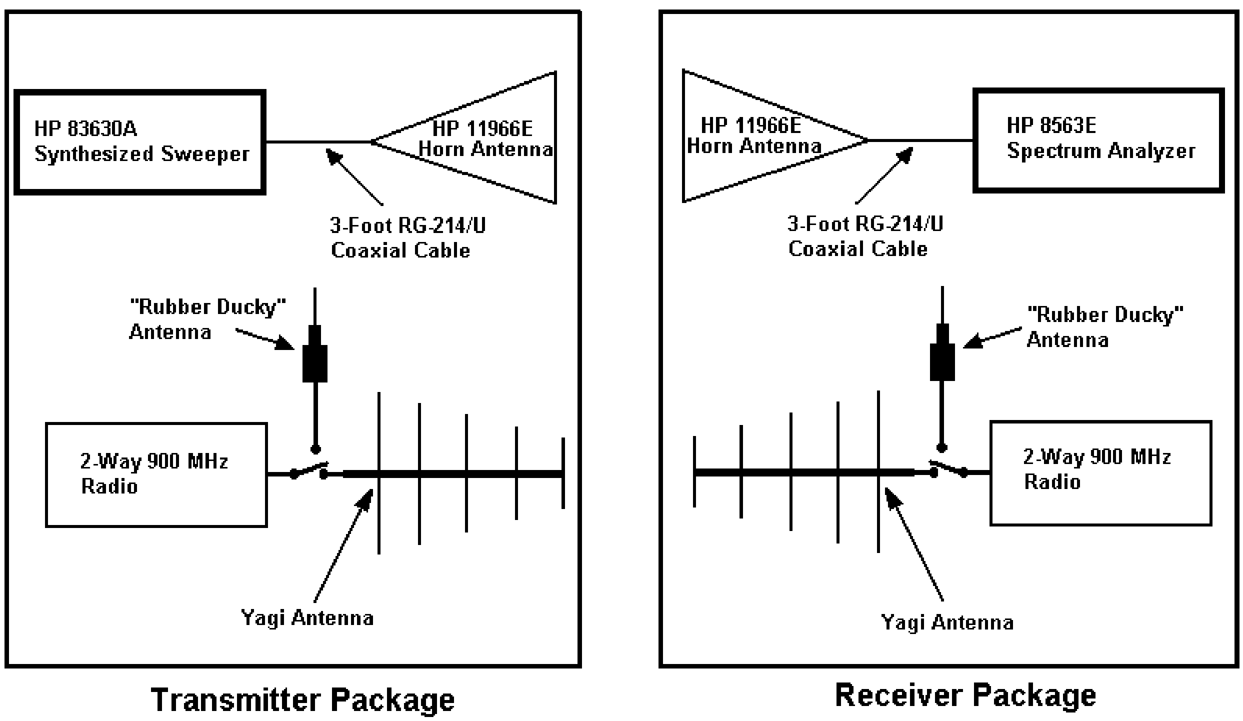
Equipment List

Transmitter Instrumentation Package

Cushcraft Model PC-8910N 896-940 MHz YAGI antenna
Motorola MT 2000 3-watt output hand-held radio operating at 936.64 MHz
HP 83630A Synthesized Sweeper
HP 11966E Waveguide Horn Antenna, 1 GHz to 18 GHz
Miscellaneous connectors, cables, multimeters

Receiver Instrumentation Package

Cushcraft Model PC-8910N 896-940 MHz YAGI antenna
Motorola MT 2000 3-watt output hand-held radio operating at 936.64 MHz
HP 11966E Waveguide Horn Antenna, 1 GHz to 18 GHz
Hewlett Packard Model 8563E Portable Spectrum Analyzer, 9 kHz to 26.5 GHz
Miscellaneous connectors, cables, multimeters



Test Equipment Arrangement
Figure A-1

At Soap Lake Siphon the receiver package was fixed and located inside the siphon outlet structure, while the transmitter package was mobile and moved to the various test positions. At Azotea tunnel the transmitter package was fixed and located inside the tunnel entrance, while the receiver package was mobile and moved to the various test positions.

APPENDIX B

ANTENNA GAIN
CALCULATION PROCEDURES FOR:
EQUIVALENT ISOTROPIC-ANTENNA SIGNAL STRENGTH
FREE-SPACE SIGNAL STRENGTH

ANTENNA GAIN AND EQUIVALENT ISOTROPIC-ANTENNA RECEIVED SIGNAL STRENGTH

Antenna Gain

All measurements were made with an HP 11966E Waveguide Horn antenna on both the transmitting and receiving packages. A chart of antenna gain was supplied with the antenna, but the lowest frequency in that chart was 1000 MHz (1.0 GHz). Table B-1 contains the data from the antenna chart for the frequencies above 1.0 GHz used in these tests. A frequency of 900 MHz is close enough to 1000 MHz that estimating the antenna gain is feasible, but 600 MHz is too low for a reasonable estimate, as the gain is falling rapidly as the frequency drops (upper cutoff frequency region). For 900 MHz, the antenna gain was extrapolated from the provided data using the SPSS, Inc. TableCurve 2D v.4 program.

TABLE B-1
Antenna Gains for HP 11966E Waveguide Horn Antenna

Frequency (MHz)	Antenna Factor (db)
600	N/A
900	7.0 Estimated
2000	8.6
6000	11.1
11000	12.2
16000	15.9

Calculation Procedure for Equivalent Isotropic-Antenna Signal Strength

To calculate the equivalent isotropic-antenna signal strength, it is necessary to take the measured signal strength in dBm and subtract both the transmitting and receiving antenna gains in dB. In these tests the same make and model antenna were used at both the transmitter and receiver, so the antenna gain is the same for both the transmitting and receiving antennas. Therefore, the formula is:

$$S_I = S_R - 2G_A$$

where

S_I = Isotropic Signal Strength in dBm
S_R = Received Signal Strength in dBm
G_A = Antenna Gain in dB

For example, from Table C-1, at 10 feet separation between the transmitter and receiver packages, at 2.0 GHz the received signal strength was -22.0 dBm. From Table B-1 below, the antenna gain is 28.4 db. Therefore, the equivalent isotropic-antenna received power level would be:

$$S_I = -22.0\text{dBm} - 2(28.4) = -78.8 \text{ dBm}$$

This number (-78.8 dBm) would be used when the absolute, isotropic-antenna- referred signal-strength is needed. An example would be the comparison of the receiver signal strength at some distance down a tunnel with the received signal strength in open air (approximately that of free space).

Calculation Procedure for Free-Space Signal Strength

The equation[1] for free-space attenuation is:

$$\alpha = 36.6 + 20\log f + 20\log d$$

where

α = free-space attenuation in dB
f = frequency in MHz
d = distance in miles

For these tests, d is reported in feet. If d is in feet, the equation becomes

$$\alpha = 20\log f + 20\log d - 37.9$$

Since the output power of the microwave signal source used in these tests was +10 dBm, the free-space signal strength, S in dBm, will be:

$$S = 10 - \alpha$$

1. **Reference Data for Radio Engineers** (Howard W. Sams & Co., Inc., 1975): 28-19.

APPENDIX C

MEASURED SIGNAL STRENGTH DATA

Table C-1
Baseline Signal Strength Measurements

Distance, ft.	Signal Strength, dBm[1] 600 MHz	900 MHz	2.0 GHz	6.0 GHz	11.0 GHz	16.0 GHz
10	-38.00	-18.00	-22.00	-27.50	-31.70	-32.20
1,000	-83.00	-65.50	-65.70	-67.00	-66.20	-70.00
2,250	-101.00	-75.30	-84.80	-85.30	-85.00	-83.80
3,040	-110.00	-95.00	-84.80	-87.00	-88.00	-88.30

Table C-2
Soap Lake Siphon Signal Strength Measurements

Location (see Appendix D)	Distance ft.	Signal Strength, dBm[1] 600 MHz	900 MHz	2.0 GHz	6.0 GHz	11.0 GHz	16.0 GHz
1	100	-57.00	-36.00	-39.00	-46.00	-49.00	-54.00
2	2,200	-102.00	-61.00	-61.00	-71.00	-79.00	-79.00
3	2,900	-94.00	-74.00	-84.00	-85.00	-95.00	-97.00
4	5.700	-115.00	-107.00	-109.00	-115.00	-110.00	Note 3

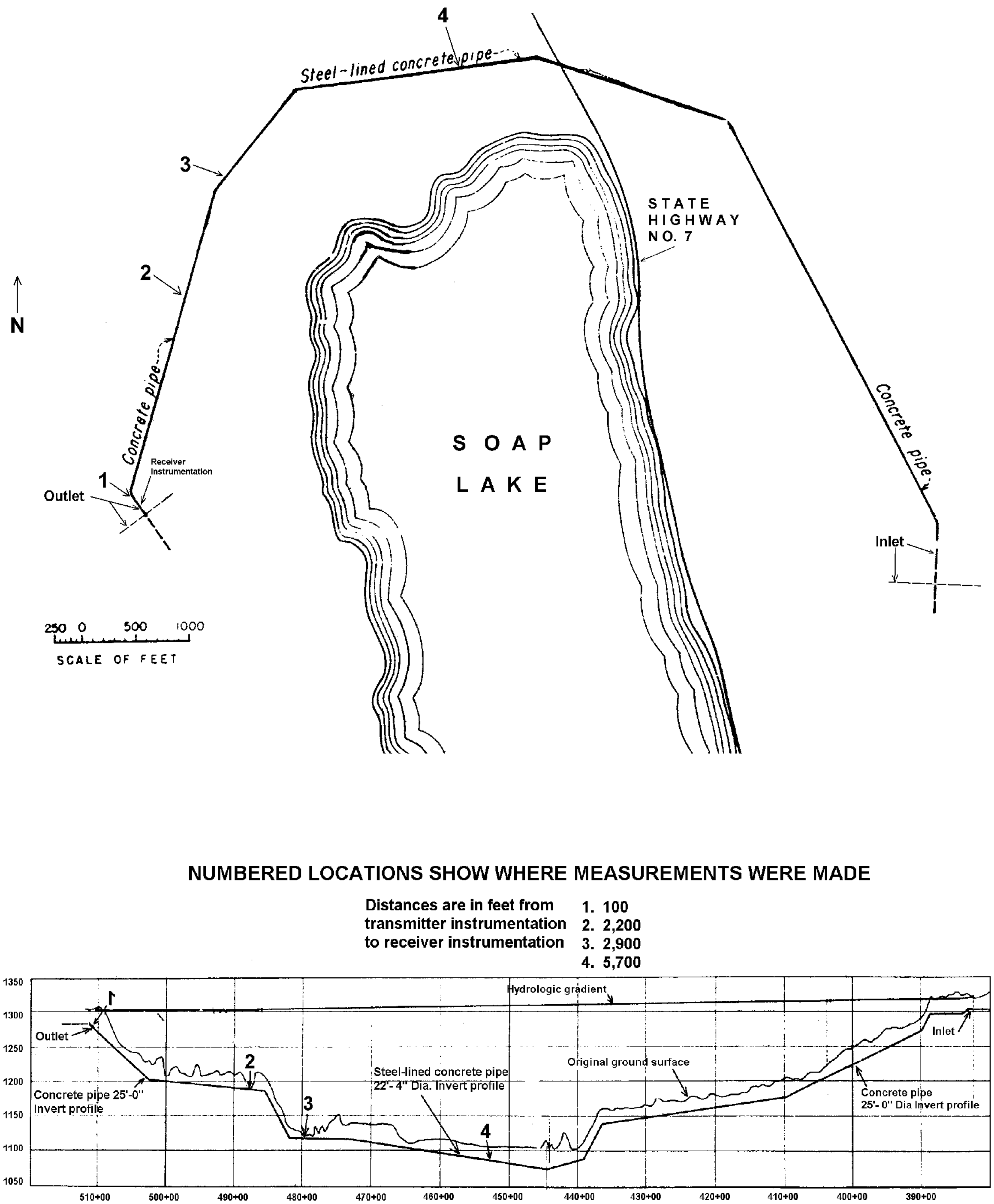
Table C-3
Azotea Tunnel Signal Strength Measurements

Station Number[2]	Distance ft.	Signal Strength, dBm[1] 600 MHz	900 MHz	2.0 GHz	6.0 GHz	11.0 GHz	16.0 GHz
750	150	-56.00	-40.00	-38.00	-51.00	-47.00	-55.00
760	1,150	-107.00	-59.00	-46.00	-48.00	-50.00	-57.00
770	2,150	Note 3	-85.00	-48.00	-48.00	-52.00	-62.00
780	3,150		-100.00	-52.00	-54.00	-60.00	-59.00
790	4,150		-106.00	-57.00	-56.00	-62.00	-67.00
800	5,150		-116.00	-63.00	-54.00	-63.00	-59.00
810	6,150		-122.00	-68.00	-55.00	-57.00	-69.00
830	8,150		Note 3	-77.00	-58.00	-59.00	-72.00
850	10,150			-86.00	-57.00	-63.00	-62.00
900	15,150			-115.00	-61.00	-66.00	-66.00
910	16,150			Note 3	-62.00	-69.00	-72.00
920	17,150				-61.00	-67.00	-66.00

1. The signal strength numbers include the gain of the horn antennas at both the transmitter and receiver. The power output to the transmitting horn antenna was +10 dBm.
2. Station numbers identify specific locations 100 feet apart along a water conveyance. The distance between two station numbers is the difference between the numbers multiplied by 100 feet.
3. The signal was too small to be measured with the available equipment. Measurements were not made at larger distances.

APPENDIX D

SOAP LAKE SIPHON DIAGRAM



SOAP LAKE SIPHON

Figure D-1

APPENDIX E

PHOTOGRAPHS:

FREE-SPACE MEASUREMENT TEST EQUIPMENT SETUP

AZOTEA TUNNEL AND TEST EQUIPMENT SETUP

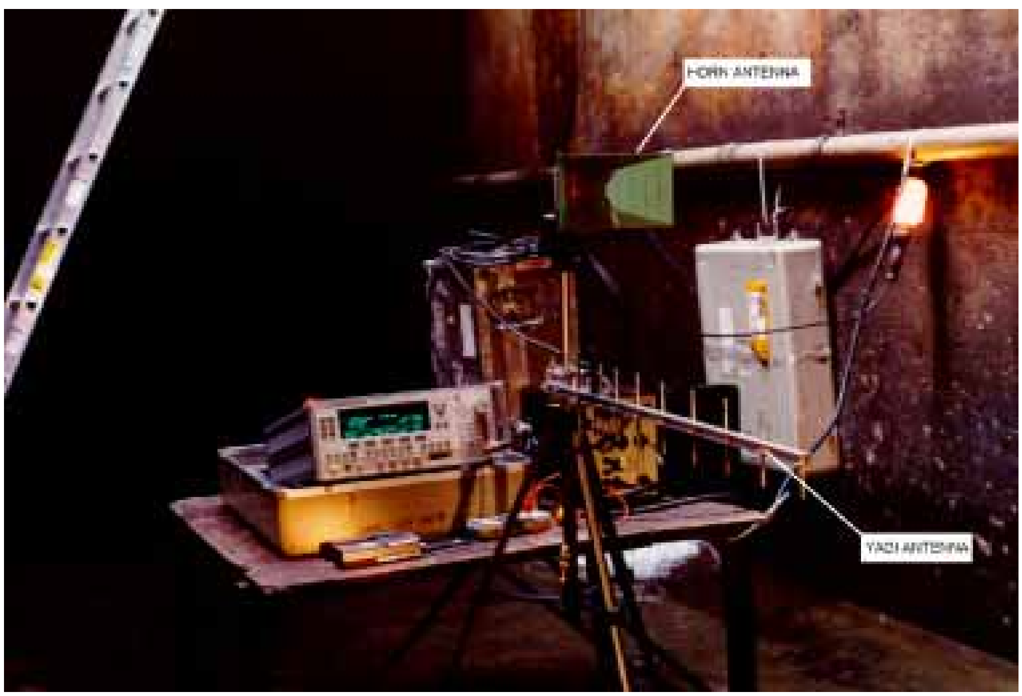
Transmitter Setup for Benchmark Signal Strength Measurements

Figure E-1

Removing the Cover for Access to the Azotea Tunnel

Figure E-2

Azotea Tunnel Entrance and Transmitter Setup
Notice the water along the tunnel bottom
Figure E-3



Azotea Tunnel entrance Transmitter Instrumentation
The horn antenna is mounted above the YAGI antenna
Figure E-4

Receiver Instrumentation on Vehicle

Figure E-5

900-MHz High-Gain YAGI Antenna Mounted on Vehicle

Figure E-6

Closeup of Receiving Equipment with Horn Antenna

Figure E-7

APPENDIX F

BACKGROUND DOCUMENTS

Excerpt from William C. Jakes, **Microwave Mobile Communication**: 110-113

2.2.9 signal Attenuation in Tunnels

It is well known that frequencies in the VHF region commonly used for mobile communications are severely attenuated in tunnel structures.[36,37] Only by using special antennas are these frequencies usable in long (over 1000 ft) tunnels. However, at microwave frequencies tunnels are effective guiding or channeling mechanisms and can offer significant improvement over VHF for communications.

A test[38] was performed in the center tube of the Lincoln Tunnel, 8000 ft. long, which connects midtown Manhattan to New jersey under the Hudson River. The inside of the tunnel is roughly rectangular in cross section with a height of 13.5 ft and width of 25 ft. Seven test frequencies roughly an octave apart were used to make signal attenuation measurements at the following frequencies: 153, 300, 600, 900, 2400, 6000, and 11,215 Mhz. The transmitters were stationed 1000 ft inside the western portal in order to keep the test situation as simple as possible. This location cleared an initial curve at the entrance and allowed a line-of-sight path of nearly 2000 ft before an elevation change cut off the view. Beyond this point nearly another mile of tunnel remained before the eastern exit was reached.

The average loss of signal strength in dB against the antenna separation for the seven frequencies is plotted in Figure 2.2-26. For convenience in plotting the data, an arbitrary reference level of 0dB at 1000 ft antenna separation was chosen. It is worth noting that the 153- and 300-Mhz attenuation rates are nearly straight lines, implying that the signal attenuation has an exponential relationship to the separation. At 153 Mhz the loss is extremely high (in excess of 40 dB per 1000 ft), where at 300 Mhz the rate of attenuation is of the order of 20 dB per 1000 ft. At higher frequencies a simple exponential attenuation rate is not evident. In Figure 2.2-27 the dqta have been replotted on a logarithmic distance scale. Signal attenuations that depend upon distance raised to some power appear as straight lines in this case. For the major portion of the length of the tunnel, the received signal level at 900 Mhz has an inverse fourth-power dependence upon the antenna separation, while at 2400 Mhz, dependance of the signal strength with antenna separation is less than the free-space path loss (throughout most of the length of the tunnel. Roughly, the attenuation rates appear to be only 2-4 dB per 1000 ft for frequencies in the 2400-11,000 MHz range.

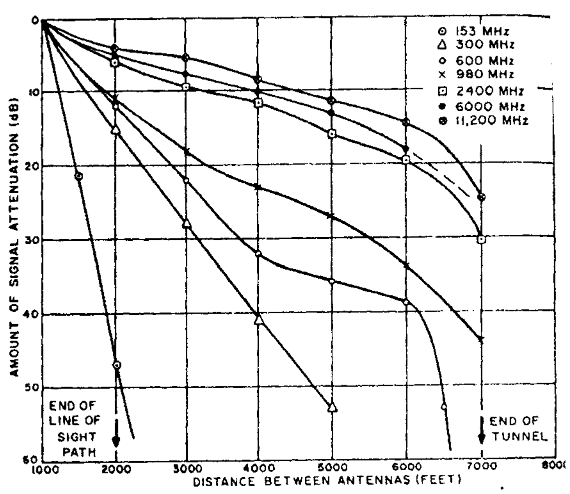


Figure 2.2-26 Signal loss versus antenna separation for seven frequencies.

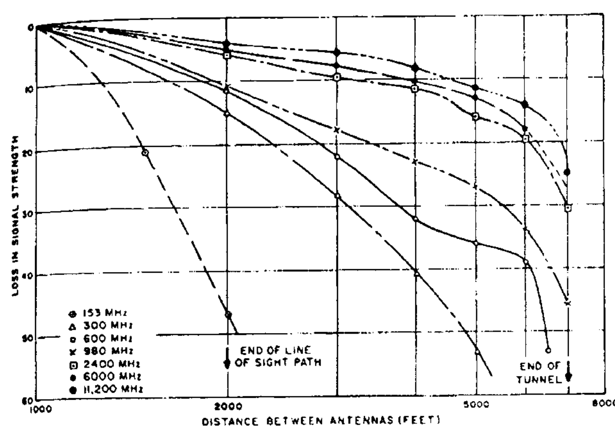


Figure 2.2-27 Signal loss versus log of antenna separation for seven frequencies.

3.3.8.4 Tunnel

Microwave frequencies are substantially attenuated by the structure of tunnels. This attenation can reach 20 dB or more, greatly affecting radio communication. On the other hand, tunnels may work as wave guides, channeling the radio signal. Reudink[18] carried out an investigation where he placed a transmitter at approximately 300 m inside a tunnel, taking measurements at a distance of 600 m inside the tunnel in a line-of-sight path. Some of his results are shown in Figure 3.18.

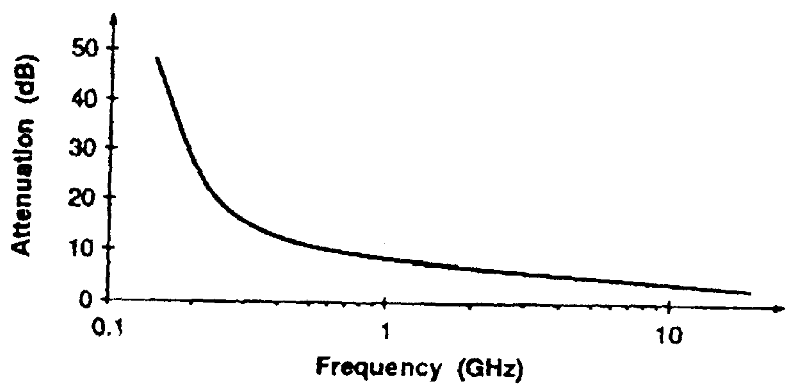


Figure 3.18. Attenuation in a tunnel. (*Source:* W. C. Jakes, *Microwave Mobile Communications*, John Wiley & Sons, New York, 1974.)

Excerpts from
WATER OPERATION AND MAINTENANCE
Bulletin No. 166: 15-18
December 1993

Probing the Depths of Reclamation Tunnels
by Bill Bouley

With over 275 miles of water distribution tunnels administered by the Bureau of Reclamation in the western United States, the pressure is on operation and maintenance personnel to keep the system running. To ensure that there are no unanticipated emergencies, the Review of Operation and maintenance (RO&M) Program and annual project reviews are used to examine tunnel interiors after water deliveries have been concluded each water year to identify areas needing special attention prior to initiating waterflows the following water delivery season.

On the Colorado-Big Thompson Project, Gene Price of the Eastern Colorado Projects Office uses a diesel-fueled jeep equipped with a detergent exhaust scrubber to transport examination personnel into the larger tunnels in their projects area. The automobile is generally reliable, except once when a television news crew was allowed to film the tunnel trip through Alva B. Adams Tunnel. On that occasion, after the RO&M team completed its examination, the news crew climbed aboard to film the tunnel. Unfortunately, for the crew, the radiator fan broke free of its mounting and damaged the radiator, shutting the jeep down. The group had a choice – walk 5 miles uphill in the tunnel to the locked west portal or walk 8 miles downhill to the open east portal. Naturally, they chose to walk downhill, with the wind at their backs.

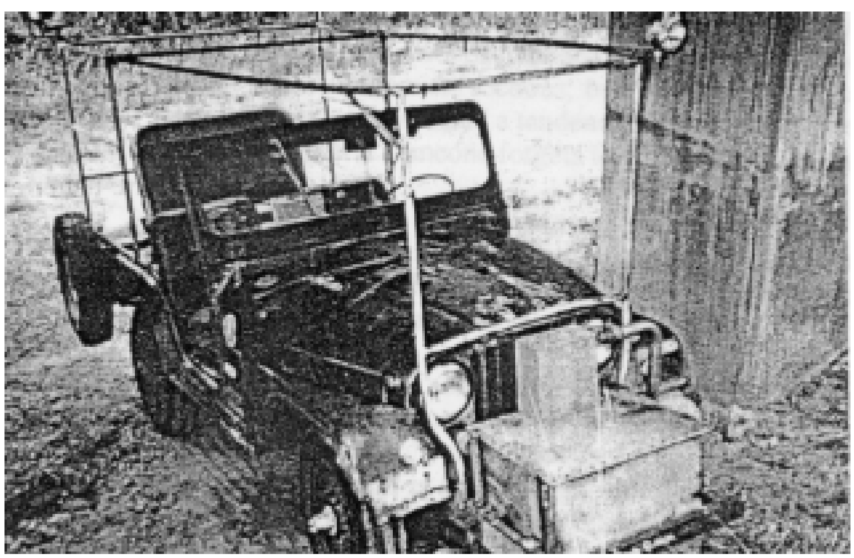


Photo 1. - Diesel-fueled jeep used in larger tunnels.

The largest tunnel in the

California Central Valley Project is the 17.5-foot-diameter, 10-mile-long Clear Creek tunnel. Water flows from the Trinity River watershed through the tunnel to the 150-megawatt Judge Francis Carr powerplant and the Sacramento River near the city of Redding. At one point, the tunnel is 2,735 feet below the surface and it passes through five significant fault zones. There are approximately 3,000 joints in the reinforced-concrete lining. Ridges tend to grow at each joint. The ridges grow to no more than ½ to 3/4 inch high; however the sum of their resistance is enough to reduce the maximum output of the powerplant by 6 megawatts. For the above reasons, it is important to periodically inspect the tunnel.

The mode of transportation for inspecting Clear Creek Tunnel is a 1941 diesel-fueled jeep equipped with a catalytic exhaust gas scrubber. The jeep is lowered down the air shaft near the inlet of the tunnel and driven in reverse for 10 miles to the Crystal Creek Adit. The inspection team can exit the tunnel at that point and the jeep is normally driven back the next day.

The following is a true story of one inspection as described by Bill Nixon, Mid-Pacific Regional Office:

> Safety is the number one item. The tunnel was dewatered. The job hazard analysis had been laboriously reviewed many times. The oxygen sensor was working; it always worked "before" starting down the tunnel. The air velocity was measured and recorded. The jeep was placed in the tunnel. A ladder was attached to the jeep so that the top of the tunnel could be examined. The men with all sorts of safety equipment were on board. The engine started and the party drove away. One hundred yards down range, the engine died. Extensive investigation determined that no one had thought to put **fuel** in the jeep!

The San Juan-Chama Project has a series of tunnels totaling over 16 miles in length. The Chama Field Office uses a three-wheeled modified electric cart to inspect the tunnel interiors. On a recent RO&M, the Albuquerque Projects Office also rented a four-wheeled electric (golf) cart to assist in the inspection which required a survey of tunnel invert erosion (see Bulletin No. 162, pp. 48-50), and cracks in the concrete lining. Because of the circular cross section, a template was used to measure eroded and offset lining. The three-wheeled cart straddled the eroded invert sections; but, when driven by an operator unaccustomed to tunnel work far from the light of day, it had a tendency to ride up the sides of the tunnels. The other disadvantage to electric carts is that if someone forgets to recharge the batteries, one may have to walk out of the tunnels.

The Provo Projects Office uses a more environmentally conscious approach in examining tunnels in its projects area. They use mountain bikes (hopefully going downhill). The disadvantage to this method may be the wet streaks one gets if he does not use raingear.

Other tunnels, such as Tecolote Tunnel in the Cachuma Project, are walked on foot due to the number of hot water springs which enter the tunnel. Because of the hot springs, there is a potential hazard of hydrogen sulfide gas and explosive gases. A physical examination is required to certify fitness for the tunnel examination walk, but a safety wagon is still brought along in case someone succumbs to the effort required to walk through the heat and humidity of the tunnel.

Air quality is evaluated prior to any tunnel inspection to determine the need for personal breathing apparatus. Canister-type air-monitoring devices are more effective where water spray is a problem. Monitors detecting levels of explosive gases, oxygen content, and presence of hydrogen sulfide have been used to ensure air suitability. It is no fun being a “mole” if you cannot stop and smell the concrete or rock lining.

Itineraries are left with surface crews to watch for the exit of the examination teams from the tunnels. This is because radio communications from inside a tunnel are not usually feasible. On shorter tunnels, air horns could be used to broadcast a predetermined distress signal to crews waiting at the exit portal.

Additional technical information on tunnel examinations may be found in Reclamation’s “Review of Operation and Maintenance Program Field Examination Guidelines,” October 1991. This publication is available from the”Publications for Sale” booklet, Bureau of Reclamation, Attention: D-7923H, PO Box 25007, Denver CO 80225; price $3.30 plus postage.

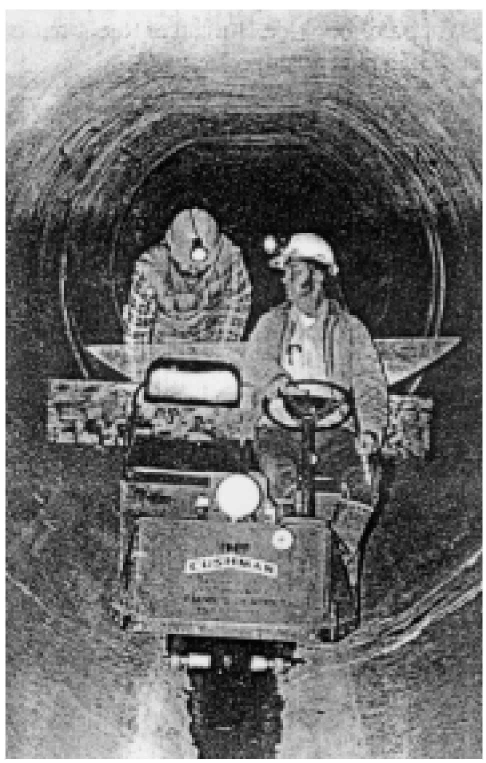


Photo 2. - Modified electric cart used in RO&M exam.

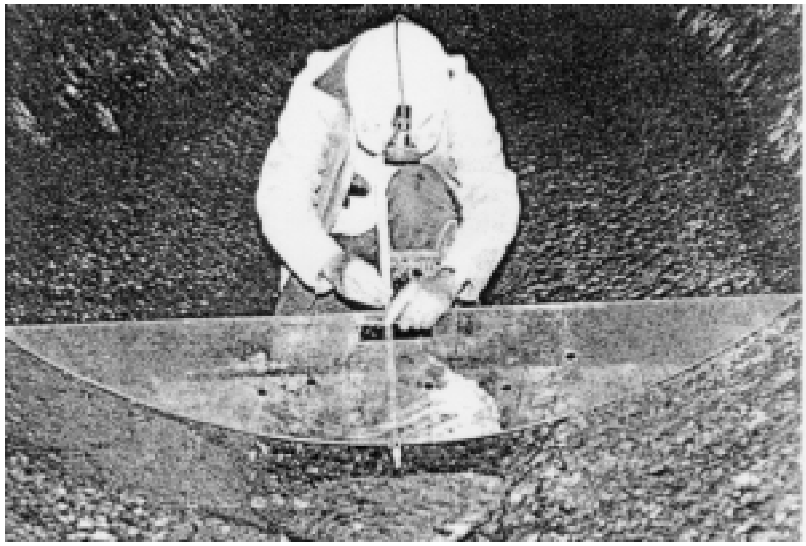


Photo 3. - Measuring the tunnel invert erosion using template and measuring device.

PEER REVIEW DOCUMENTATION

PROJECT AND DOCUMENT INFORMATION

Project Name Technology Maturation Funding - Tunnel Communications WOID PMME3

Document Project Notes 8450-98-06 Tunnel Communications - Test Results

Document Date January 1998 Date Transmitted to Client OCT 16 1998

Team Leader Phil Atwater Leadership Team Member ________
(Peer Reviewer of Peer Review/QA Plan)

Peer Reviewer Phil Atwater Document Author(s)/Preparer(s) J. DeHaan
M. L. Jacobs

Bert Milano

REVIEW REQUIREMENT

Part A: Document Does Not Require Peer Review

Explain ________

Part B: Document Requires Peer Review: SCOPE OF PEER REVIEW

Peer Review restricted to the following Items/Section(s): Reviewer:

Technical adequacy	Phil Atwater
Group policies	Bert Milano

REVIEW CERTIFICATION

Peer Reviewer - I have reviewed the assigned Items/Section(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer: Phil Atwater Review Date: 3-17-98
Signature

Reviewer: Bert Milano Review Date: 9/30/98
Signature

Preparer - I have discussed the above document and review requirements with the Peer Reviewer and believe that this review is completed, and that the document will meet the requirements of the project.

Team Member: Marlin L. Jacobs Date: 3/17/98
Signature